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TIME DOMAIN SCATTERING OF FOCUSED ELECTROMAGNETIC BEAM BY LOSSY TARGETS

FINAL REPORT

by

Kenneth K. Mei

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ELECTRONICS RESEARCH LABORATORY

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| 19. ABSTRACT (Continue on reverse if necessary and identify by block number) The specific purpose of this research investigation is to study the scattering of focused electromagnetic beam by lossy targets. The broader objective of this study is the general application of time domain computations. So, the research results of this investigation include a rather broad subjects in electromagnetics. They are related to applications of time domain analyses of focused beam, lossy medium, microstrips and microwave components, absorbing boundary conditions and superconductors. | | | | | | |
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Introduction

The specific purpose of this research contract is to study the scattering of focused electromagnetic beams by lossy targets. This objective has been duly accomplished, and as a result of an elaborate study of the subject in a Ph.D dissertation. The broader objective of this research study is the general application of time domain computational techniques in electromagnetic theory. That general objective is also accomplished in numerous papers published and presented in the area of time domain methods.

Accomplishments

The general objective of this contract is the study of the application of time domain techniques in electromagnetic computation. We have used the specific goal of understanding the interaction of focused beam with lossy media to isolate many important issues associated with time domain computations yet can also be applied to other areas, notably, microstrips and MMIC related computations. Those issues are:

(1) *Absorbing Boundary Conditions*

In the computation of open systems, the finite difference or finite element meshes must be terminated by an artificial absorbing boundary condition which simulates a non-reflective boundary. Since this is such an important issue with time domain computation, the absorbing boundary is indeed a part of differential equation approach to scattering problems. There are many ways an absorption condition can be implemented. Some absorbing conditions are easy to apply but do not absorb well and some absorbing conditions absorb well, but are not so easy to apply.

In our investigation, we have invented a procedure termed "Superabsorption." This method can improve any existing absorbing boundary condition by an order of magnitude with very simple programming procedures. It is indeed a breakthrough in the study of absorbing boundary conditions.

(2) *Propagation Along Interfaces*

The time domain investigation of wave propagation along dielectric interfaces is another important issue in TD computation. A typical such problem is a microstrip at high frequencies when the quasistatic results fail. We have used the time domain method to investigate the performance of microstrips and other MMIC components.

(3) *Penetration of Focused Beam into Lossy Media*

The penetration of focused beam is an effort to find out whether the temperature of a body can be raised in the interior without overheating the exterior. This is an issue most interested by those interested in biological effects of microwaves and hyperthermia. Our computation shows that it is possible to make a hot spot using focused beam.

(4) *Computations Involving Superconductive Material*

There are many experiments now going on regarding the application of superconductors in microwave and mm-waves. Indications are, one day this material will be used in many devices. Any serious application of this material will involve computations. How should we treat this material? Is a superconductor the same as a perfect conductor? These questions are answered in our paper on "Electromagnetics of Superconductors."

In the following pages, we have listed the abstract of the papers that have been published or presented under the sponsorship of this contract.

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Journal Articles

- (1) "Unimoment Method for Electromagnetic Wave Scattering," *Journal of Electromagnetic Waves and Applications*, vol. 1, no. 4, pp. 321-342, 1987.
- (2) "Point-Matched Time Domain Finite Element Methods for Electromagnetic Radiation and Scattering," *IEEE Transactions on Antenna and Propagations*, vol. 35, no. 10, pp. 1160-1172, October 1987.
- (3) "Dispersion Characteristics of Microstrip Lines in the Vicinity of a Coplanar Ground," *Electronics Letters*, vol. 23, no. 21, pp. 1142-1143, October 1987.
- (4) "Calculations of the Dispersive Characteristics of Microstrip by the Time-Domain Finite Difference Method," *IEEE Transactions on Microwave Theory and Technique*, vol. 36, no. 2, pp. 263-267, February 1988.
- (5) "Time Domain Finite Difference Approach to Calculation of the Frequency-Dependent Characteristics of Microstrip Discontinuities," *IEEE Transactions on Microwave Theory and Techniques*, vol. 36, no. 12, pp. 1775-1787, December 1988.

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Unimoment Method for Electromagnetic Wave Scattering

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Abstract—A simple problem in 2-dimensional space is used as an example for the application of the unimoment method. The discussion includes fundamentals, mesh generation, loading of equations, sparse matrix inversion and boundary matching. The objective of this paper is to help uninitiated readers understand and apply this method.

Tutorial

Point-Matched Time Domain Finite Element Methods for Electromagnetic Radiation and Scattering

ANDREAS C. CANGELLARIS, MEMBER, IEEE, CHUNG-CHI LIN, MEMBER, IEEE, AND KENNETH K. MEI, FELLOW, IEEE

Abstract—Direct time domain computation of Maxwell's differential equations will soon become a practical technique because of the availability of supercomputers. The principal methods used in time domain computations and the supporting theories are presented. The point-matched finite element method is chosen as the main feature of this presentation, which includes the discretization of equations, conforming mesh generation, dielectric and metallic interfaces, numerical stability and simulation of radiation conditions. Numerical results of scattering of Gaussian pulses are presented in time sequences.

DISPERSION CHARACTERISTICS OF MICROSTRIP LINES IN THE VICINITY OF A COPLANAR GROUND

Indexing terms: Microwave circuits and systems, Microstrip

The influence of a coplanar ground on the dispersion characteristics of neighbouring microstrip is studied using the time-domain finite-difference method. Changes in characteristic impedance and propagation constant from those of ideal microstrip are obtained. Further, an imaginary part of the characteristic impedance and a non-negligible attenuation constant are detected at high frequencies.

Calculations of the Dispersive Characteristics of Microstrips by the Time-Domain Finite Difference Method

XIAOLEI ZHANG, JIAYUAN FANG, KENNETH K. MEI, FELLOW, IEEE, AND YAOWU LIU

Abstract—The dispersive characteristics of microstrips have been investigated by many authors [1]–[4] using various numerical and empirical methods. Those results showed a lack of agreement with each other, and the true dispersive characteristics of microstrips still need to be identified. In this paper, a direct time-domain finite difference method is used to recharacterize the microstrip. Maxwell's equations are discretized both in time and space and a Gaussian pulse is used to excite the microstrip. The frequency-domain design data are obtained from the Fourier transform of the calculated time-domain field values. Since this method is completely independent of all the above-mentioned investigations, the new results can be considered as an impartial verification of the published results.

The comparison of the time-domain results and those from the frequency-domain methods has shown the integrity of the time-domain computations. Since this method is very general and can be applied to model many other microwave components, its success in the microstrip problem is an important step toward its general application.

Time-Domain Finite Difference Approach to the Calculation of the Frequency-Dependent Characteristics of Microstrip Discontinuities

XIAOLEI ZHANG AND KENNETH K. MEI, FELLOW, IEEE

Abstract—The frequency-dependent characteristics of the microstrip discontinuities have previously been analyzed using several full-wave approaches. The time-domain finite difference (TD-FD) method presented in this paper is another independent approach and is relatively new in its application for obtaining the frequency-domain results for microwave components [26]. The purpose of this paper is to establish the validity of the TD-FD method in modeling circuit components for MMIC CAD applications.

Papers Presented

- (1) "Penetration of a Focused Electromagnetic Pulse into a Lossy Medium," URSI XXII General Assembly, Tel Aviv, Israel, *Digest*, p. 262, August 1987.
- (2) "To Be Or Not To Be in the Time Domain," URSI/USNC, *Spring Meeting Digest*, Denver, Colorado, p. 107, January 1988.
- (3) "Time Domain Finite Difference Approach for the Calculation of Microstrip Open Circuit," MTT Symposium, New York, May 1988.
- (4) "Super Absorbing Boundary Algorithm for Solving Electromagnetic Problem by Time Domain Finite Difference Method," IEEE Antennas and Propagation Symposium, pp. 472-476, Syracuse, NY, June 1988.
- (5) "Time Domain Finite Difference Calculation Using Variable Step Size," IEEE Antennas and Propagation Symposium, San Jose, CA, June 1989.
- (6) "Penetration of a Focused Electromagnetic Pulse into Biological Material and Its Application to Hyperthermia," IEEE Antennas and Propagation Symposium, San Jose, CA, June 1989.
- (7) "Time Domain Finite Difference Approach for Modeling of Microstrip Components," IEEE Antennas and Propagation Symposium, San Jose, CA, June 1989.
- (8) "Electromagnetics of Superconductors," Plenary Session, IEEE Antennas and Propagation Symposium, San Jose, CA, June 1989.
- (9) "A Computer Simulation of Using a Large Reflector Antenna for Microwave Hyperthermia," 1989 International Symposium on Antennas and Propagation, August 1989, Tokyo, Japan.
- (10) "Time-Domain Calculation of Microstrip Components and Curve-Fitting of Numerical Results," 1989 IEEE MTT-S International Microwave Symposium *Digest*, vol. 1, pp. 313-316, June 1989, Long Beach, CA.

PENETRATION OF A FOCUSED ELECTROMAGNETIC PULSE INTO A LOSSY MEDIUM

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Department of Electrical Engineering and Computer Sciences
and the Electronics Research Laboratory,
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Interaction of electromagnetic beam with a lossy interface is studied using a time domain finite element method. A plane wave of Gaussian pulse is transmitted towards a 2-D parabolic reflector, which causes a high intensity field around the focus, as the rest of the wave passes. When this focusing field is directed towards an air-lossing medium interface, the time sequence of the penetration of the fields into the lossy medium can be observed. If the heat conductivity and specific heat of the medium is known, the temperature profile of the lossy medium near the area of penetration can also be calculated in time sequence. This talk presents the basic numerical techniques and some recently obtained results of calculation. Further development of this project can have interesting biomedical applications.

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B4-7 TO BE OR NOT TO BE IN THE TIME DOMAIN
1620 Kenneth K. Mei
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Maxwell's differential equations in the frequency domain are elliptical, which results in classical boundary value problems. In the time domain they are hyperbolic, the solutions of which march in time. Numerically, the frequency domain differential equations require solutions of matrices; the time domain differential equations, if explicit, are spared from such endeavor. Before the coming of super computers, almost all electromagnetic problems were solved in the frequency domain. Now, there is a choice. This talk enumerates the pros and cons of computations in either domain. Depending on the objectives of the computation, one can make a rational decision in the computational domain. However, individual familiarity and personal beliefs often are the dominant factors of to be or not to be in one particular domain.

Time-Domain Calculation of Microstrip Components and the Curve-Fitting of Numerical Results

Xiaolei Zhang and Kenneth K. Mei

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Abstract

The Time-Domain Finite Difference method combined with Fourier transform techniques has recently been shown to be a very effective approach in modeling the dispersive characteristics of microstrip components[1-3]. The present research further investigate the problems associated with the generation of design data over a larger substrate and line parameter range and the curve-fitting of the numerical results for CAD purpose.

**A Super-Absorbing Boundary Algorithm For Solving Electromagnetic
Problems By Time-Domain Finite-Difference Method**

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Abstract. A new algorithm is presented to treat the absorbing boundaries for time domain finite difference method. With this approach, the leading order error of the conventional local absorbing boundary conditions can be cancelled by a simple algorithm, so that the absorbing quality of the boundary conditions can be greatly improved.

TIME DOMAIN FINITE DIFFERENCE CALCULATIONS USING A VARIABLE STEP SIZE

Svetlana Zivanovic* and Dr. Kenneth K. Mei
University of California, Berkeley

Computational electromagnetics (CEM) is becoming increasingly more prominent today, solving problems which either cannot be solved by analytical methods, or are too expensive to investigate experimentally. One such approach is the finite difference method (FDM) developed by K. Yee (ref. 1) which has been successfully used for the calculation of electromagnetic fields in various structures (ref. 2).

However, one serious drawback of FDM is that the computer memory required to obtain sufficiently accurate results approaches and often exceeds the available memory of most computers. One way around this is to use bigger and bigger computers such as the CRAY II; another is to refine FDM to decrease the needed memory while keeping the error within a tolerable limit.

This paper describes a new method which uses a variable step size (calculation increment) in the finite difference technique (VSSFDM). The step size is kept small around discontinuities and larger away from them, thereby using only about 1/3 of the memory required by a straight application of Yee's method. The results obtained by VSSFDM are very close to those obtained by FDM (ref. 2) but with a significant reduction in the required computer memory, as well as CPU time.

PENETRATION OF A FOCUSED ELECTROMAGNETIC PULSE
INTO A BIOLOGICAL MATERIAL
AND ITS APPLICATION TO HYPER THERMIA

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Abstract – A localized temperature distribution inside a biological material (human muscle) is obtained through the use of a parabolic reflector to focus an electromagnetic pulse. With the point-matched time domain finite element method, the focused field and its penetration into the biological material are found; then, the temperature profile in the material is calculated. Due to the localization property, this study can have a significant contribution to the hyperthermic therapy. The factors which influence the localization characteristics are also investigated. They are the applied frequency, the associated electric parameters of the biological material, and the size of the parabolic reflector.

Time-Domain Finite Difference Approach for the Modeling of Microstrip Components

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Abstract

The frequency-dependant characteristics of the microstrip open-end has been analysed using several full-wave approaches [1-5]. The time-domain finite difference (TD-FD) method presented in this paper is another independant approach, which is ralatively new in its application to obtain the frequency domain results [6]. The purpose of this paper is to establish the validity of the TD-FD method in modeling circuit components for MMIC-CAD applications.

ELECTROMAGNETICS OF SUPERCONDUCTORS

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With the present pace of research and development activities in superconductors, superconductive boundary value problem is suddenly a "hot" subject. To pursue this study, the electromagnetic behavior about a superconducting medium must be clearly understood. If a superconducting surface were a lossless surface (as it is at $T=0$), it would be electromagnetically almost indistinguishable from a perfecting conducting surface except that magnetic field can penetrate into the superconductor with very small penetration depth (typically 100 nm). However, at microwave frequencies a superconductor is not a lossless material, and the loss is, in fact, proportional to frequency square. Thus, is superconductor just a low loss conductor? What are the boundary conditions of superconductors?

In this paper, we will point out that electromagnetically speaking a superconductor is indeed distinguishable from a fictitious perfect conductor. A superconducting material is more conveniently be treated as a dielectric material with negative real part of dielectric constant as far as electromagnetics is concerned. By considering superconductors as a generalized dielectric material, some superconductive electromagnetic problems are simplified, since the dielectric parameter is an integral part of electromagnetic computation. It does not present any technical difficulty to existing computer programs if a dielectric constant passes from a positive value to a negative one.

In addition to the conceptual discussion of superconductive electromagnetics, this talk will also present a time-domain computational method involving dispersive media, such as superconductors or plasma. The method involves a time-domain finite-difference with system function expansion, so that no explicit convolution is required. It thus greatly reduces memory demand and CPU time.

As a consequence of this electromagnetic treatment of a superconductor, the existence of a surface wave on a superconducting surface is also predicted. It is a surface wave which is more tightly bound to the surface than the conventional surface wave.

A COMPUTER SIMULATION OF USING A LARGE REFLECTOR ANTENNA FOR MICROWAVE HYPERTHERMIA

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I. INTRODUCTION

The use of heat to cause elevated tumor temperature at 42°C or higher (hyperthermia) has received a great interest in recent years, since in general malignant cells are more sensitive to heat than normal cells in the range of 42-45°C [1]. In addition, most tumors have much less blood perfusion rate than their surrounding normal tissues have, meaning that they may be preferentially heated [2]. Thus, obtaining a localized tumor temperature has been an important task in hyperthermic therapy. However, for non-invasive treatment, it is still difficult to produce well controlled elevated temperature distributions (in the range of 42-45°C) in the tumor without overheating normal tissue. For examples, ultrasound has good localization and deep penetration into human muscle but its limitation comes from the high absorption in bone, causing bone heating. As for electromagnetic wave, people have been using divergent waves widely which often induce maximum heating on the tissue surface with an exponential decrease with depth. Although low frequency does give a good penetration, its poor focusing may still hurt the normal tissue [3]. By using a parabolic reflector to focus an electromagnetic pulse, this paper presents a way that can generate both good focusing and satisfactory penetration, meaning that an elevated tumor temperature can be obtained without overburning the surrounding normal tissue.

The approaches in this study contain the generation of focused electromagnetic pulse, the penetration of this pulse into a biological material, and the calculation of the temperature profile in the biological material. First, a plane wave of modulated Gaussian pulse is transmitted towards a three dimensional parabolic reflector, which causes a high intensity field around the focal point, as the wave passes. Next, this focusing field is directed towards a biological material, the time sequence of the penetration of the fields into the material can be observed. The above two tasks are completed by solving the Maxwell's equations with the point-matched time domain finite element method [4]. Afterwards, the temperature profile of the biological material can be calculated through the bio-heat transfer equation [5]. Furthermore, the localization properties of the temperature profile can be adjusted by varying the related parameters.

This research was supported by the Office of Naval Research Contract N00014-86-K-0420.

Time Domain Calculation of Microstrip Components and Curve Fitting of Numerical Results

Abstract

The Time Domain Finite Difference Method has been used successfully to calculate the Frequency-Dependent characteristics of microstrip components. Supercomputers are used to carry out those full wave solutions. If those data are to be used for MMIC CAD, one needs to reduce them so that they can be stored in P.C. environment. One approach is to use curve fitting techniques such that vast amount of results can be represented by appropriate approximate functions with variable parameters. This approach appears to be quite convenient for CAD applications.

Student dissertation resulted from this research:

Doctoral Dissertations

- (1) "Time Domain Finite Difference Computation for Maxwell's Equations," by Fang, Jiayuan, December 1988.
- (2) "Penetration of a Focused Electromagnetic Pulse into Biological Material and Its Application to Hyperthermia," by Chang, Hwa-Cheng, December 1988.

Master Dissertations

- (1) "On Radiation Boundary Conditions for One Dimensional Wave Equations," Master's report by Fang, Jiayuan, May 1987.
- (2) "Calculation of Dispersive Characteristics of Microstrips Using Time Domain Finite Difference Method," Master's report by Zhang, Xiao-Lai, May 1987.
- (3) "A Numerical Analysis of a Shielded Microstrip with a Finite Discontinuity," Master's report by Winnie P. Y. Yu, August 1988.
- (4) "Time Domain Finite Difference Calculations Using a Variable Step Size," Master's report by Zivanovic, Svetlana, June 1989.